

## Measurement of the Branching Fraction of $B^0$ Meson Decay to $a_1^+(1260) \pi^-$

### Abstract

We present a preliminary measurement of the branching fraction of the  $B$  meson decay  $B^0 \rightarrow a_1^+(1260) \pi^-$  with  $a_1^+(1260) \rightarrow \pi^+ \pi^+ \pi^-$ . The data sample corresponds to  $218 \times 10^6$   $B\bar{B}$  pairs produced in  $e^+e^-$  annihilation through the  $\Upsilon(4S)$  resonance. We find the branching fraction  $(40.2 \pm 3.9 \pm 3.9) \times 10^{-6}$ , where the first error quoted is statistical and the second is systematic. The fitted values of the  $a_1(1260)$  parameters are  $m_{a_1} = 1.22 \pm 0.02$  GeV/ $c^2$  and  $\Gamma_{a_1} = 0.423 \pm 0.050$  GeV/ $c^2$ .

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# 1 INTRODUCTION

We report on the preliminary measurement of the branching fraction  $B^0 \rightarrow a_1^+(1260)\pi^-$  with  $a_1^+(1260) \rightarrow \pi^+\pi^+\pi^-$  [1]. The  $a_1(1260) \rightarrow 3\pi$  decay proceeds mainly through the intermediate states  $(\pi\pi)_\rho\pi$  and  $(\pi\pi)_\sigma\pi$  [2].

The study of this decay mode is complicated by open questions on the parameters of the  $a_1(1260)$  meson. There are large discrepancies between these parameters when comparing results from analyses involving hadronic interactions [3] and  $\tau$  decays [4]. Therefore, it is important to verify the theoretical prediction of the branching fraction for this decay mode and have new measurements of the  $a_1(1260)$  parameters. A theoretical calculation of the branching fraction of this decay mode has been made by Bauer, Stech and Wirbel (BSW) [5] within the framework of the factorisation model. They predict a value of  $38 \times 10^{-6}$ , assuming  $|\frac{V_{ub}}{V_{cb}}| = 0.08$ . It is also important to note that the  $B^0 \rightarrow a_1^+(1260)\pi^-$  channel can be used to measure the Cabibbo-Kobayashi-Maskawa angle  $\alpha$  of the Unitarity triangle [6]. We presented a preliminary version of this analysis at ICHEP'04 [7], using an integrated luminosity of  $112fb^{-1}$  and the measured branching fraction was  $(42.6 \pm 4.2 \pm 4.1) \times 10^{-6}$ . For the branching fraction of  $B^0 \rightarrow a_1^+(1260)\pi^-$  an upper limit of  $49 \times 10^{-5}$  at the 90% confidence level (C.L.) has been set by CLEO collaboration [8] while the DELPHI collaboration [9] has set the 90% C.L. upper limit of  $28 \times 10^{-5}$  for the branching fraction of  $B^0 \rightarrow 4\pi$ .

Below we present the details of the analysis for the measurement of the branching fraction for  $B^0 \rightarrow a_1^+(1260)\pi^- \rightarrow 2\pi^+2\pi^-$ . Presently, we do not distinguish between the final states  $(\pi\pi)_\rho\pi$  and  $(\pi\pi)_\sigma\pi$ . Such an analysis would require a study of the angular distributions of the decay products. Possible background contributions from  $B^0$  decays to  $a_2^+(1320)\pi^-$  and  $\pi^+(1300)\pi^-$  are studied and taken into account while in the preliminary version presented at ICHEP'04 they were neglected.

# 2 THE BABAR DETECTOR AND DATASET

The results presented in this paper are based on data collected in 1999–2004 with the BABAR detector [10] at the PEP-II asymmetric  $e^+e^-$  collider [11] located at the Stanford Linear Accelerator Center. An integrated luminosity of  $198fb^{-1}$ , corresponding to 218 million  $B\bar{B}$  pairs, was recorded at the  $\Upsilon(4S)$  resonance (“on-resonance”, center-of-mass energy  $\sqrt{s} = 10.58$  GeV). An additional  $15fb^{-1}$  were taken about 40 MeV below this energy (“off-resonance”) for the study of continuum background in which a light or charm quark pair is produced instead of an  $\Upsilon(4S)$ .

The asymmetric beam configuration in the laboratory frame provides a boost of  $\beta\gamma = 0.56$  to the  $\Upsilon(4S)$ . Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker, consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in the 1.5-T magnetic field of a solenoid. The tracking system covers 92% of the solid angle in the center-of-mass frame.

Charged-particle identification is provided by the average energy loss ( $dE/dx$ ) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A  $K/\pi$  separation of better than four standard deviations ( $\sigma$ ) is achieved for momenta below 3 GeV/c, decreasing to 2.5  $\sigma$  at the highest momenta in the  $B$  decay final states. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter while muons are identified in the magnetic flux return system.



### 3 ANALYSIS METHOD

Monte Carlo (MC) simulations [12] of the signal decay mode, of continuum and  $B\overline{B}$  backgrounds are used to establish the event selection criteria. We make several particle identification requirements to ensure the identity of all signal pions. For the bachelor charged track we require an associated DIRC Cherenkov angle between  $-2\sigma$  and  $+5\sigma$  from the expected value for a pion. A  $B$  meson candidate is characterized kinematically by the energy-substituted mass  $m_{\text{ES}} = \sqrt{(\frac{1}{2}s + \mathbf{p}_0 \cdot \mathbf{p}_B)^2 / E_0^2 - \mathbf{p}_B^2}$  and energy difference  $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$ , where the subscripts 0 and  $B$  refer to the initial  $\Upsilon(4S)$  and to the  $B$  candidate in the lab-frame, respectively, and the asterisk denotes the  $\Upsilon(4S)$  frame. We require  $|\Delta E| \leq 0.2$  GeV and  $5.25 \leq m_{\text{ES}} \leq 5.29$  GeV/ $c^2$ . We select  $a_1^+(1260)$  candidates with the following requirement on the invariant mass:  $0.8 < m_{a_1} < 1.8$  GeV/ $c^2$ . The intermediate dipion state is required to have an invariant mass between 0.51 and 1.1 GeV/ $c^2$ . The momentum of  $a_1^+(1260)$  in the center-of-mass frame is required to be between 2.3 and 2.7 GeV/ $c$ . To reduce fake  $B$  meson candidates we require  $p(\chi^2) > 0.01$  for the  $B$  vertex fit. The angular variable  $\mathcal{H}_{a_1}$  (cosine of the angle between the direction of the bachelor  $\pi$  and the flight direction of the  $B$  in the  $a_1(1260)$  meson rest frame) is required to be between  $-0.85$  and  $0.85$  to suppress combinatorics.

To reject continuum background, we make use of the angle  $\theta_T$  between the thrust axis of the  $B$  candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of  $\cos \theta_T$  is sharply peaked near  $\pm 1$  for combinations drawn from jet-like  $q\bar{q}$  pairs and is nearly uniform for the isotropic  $B$  meson decays; we require  $|\cos \theta_T| < 0.65$ . The remaining continuum background is modelled from “off-resonance” data. We use Monte Carlo simulations of  $B^0\overline{B}^0$  and  $B^+B^-$  decays to look for  $B\overline{B}$  backgrounds, which can come from both charmless and charm decays. We find that the decay mode  $B^0 \rightarrow D^-\pi^+$ , with  $D^- \rightarrow K^+\pi^-\pi^-$  and  $D^- \rightarrow K_S^0\pi^-$ , is the only significant background. It is included in the maximum likelihood fit. Final results have been corrected for a small background contribution due to charmless decays.

We use an unbinned multivariate maximum-likelihood fit to extract the signal yields for  $B^0 \rightarrow a_1^+(1260)\pi^-$ . The likelihood function incorporates five variables. We describe the  $B$  decay kinematics using:  $\Delta E$ ,  $m_{\text{ES}}$ ,  $m_{a_1}$ , a Fisher discriminant  $\mathcal{F}$ , and an angular variable A. The Fisher discriminant combines four variables: the angles in the  $\Upsilon(4S)$  frame of the  $B$  momentum and  $B$  thrust axis with respect to the beam axis, and the zeroth and second angular moments  $L_{0,2}$  of the energy flow around the  $B$  thrust axis. The moments are defined by

$$L_j = \sum_i p_i |\cos \theta_i|^j, \quad (1)$$

where  $p_i$  is the momentum of particle  $i$ ,  $\theta_i$  is the angle between the direction of particle  $i$  and the thrust axis of the  $B$  candidate and the sum excludes tracks and clusters used to build the  $B$  candidate. We have used an angular variable A in order to distinguish  $a_1^+(1260)\pi^-$  from  $a_2^+(1320)\pi^-$  and  $\pi^+(1300)\pi^-$ . If X is our resonance  $a_1(J^P = 1^+)$ ,  $a_2(J^P = 2^+)$  or  $\pi(1300)(J^P = 0^-)$  that decays into three pions, we evaluate in the X meson rest frame the cosine of the angle between the normal to the plane of the three pions and the flight direction of the bachelor pion. Since we have on average 1.5 B candidates per event, we choose the best one using a  $\chi^2$  quantity computed with the  $\rho$  mass. Since the maximum correlation between the observables in the selected data is 4%, we take the probability density function (PDF) for each event to be a product of the PDFs for the separate observables. The product PDF for event  $i$  and hypothesis  $j$ , where  $j$  can be signal (3 types), continuum background or  $B\overline{B}$  background, is given by

$$\mathcal{P}_j^i = \mathcal{P}_j(m_{\text{ES}}) \cdot \mathcal{P}_j(\Delta E) \cdot \mathcal{P}_j(\mathcal{F}) \cdot \mathcal{P}_j(m_{a_1}) \cdot \mathcal{P}_j(A). \quad (2)$$

There is the possibility that a track from a signal candidate is exchanged with a track from the rest of the event. We call these events “self-cross-feed” (SCF) events. The fraction of SCF events with respect to the total number of signal events for each type  $k$  of signal,  $f_{SCF_k}$ , is fixed to the value found with Monte Carlo signal events (26%). The likelihood function for the event  $i$  is defined as :

$$\mathcal{L}^i = \sum_{k=1}^3 \left( n_k (1 - f_{SCF_k}) \mathcal{P}_k^i + n_k f_{SCF_k} \mathcal{P}_{SCF_k}^i \right) + n_{q\bar{q}} \mathcal{P}_{q\bar{q}}^i + n_{B\bar{B}1} \mathcal{P}_{B\bar{B}1}^i + n_{B\bar{B}2} \mathcal{P}_{B\bar{B}2}^i, \quad (3)$$

where  $n_k$  ( $k = 1, 3$ ) is the yield for  $a_1^+(1260) \pi^-$ ,  $a_2^+(1320) \pi^-$ , and  $\pi^+(1300) \pi^-$  respectively,  $n_{q\bar{q}}$  the number of continuum background events,  $n_{B\bar{B}1}$  the number of  $B\bar{B}$  background events  $D^- \pi^+$  with  $D^- \rightarrow K^+ \pi^- \pi^-$  and  $n_{B\bar{B}2}$  the number of  $B\bar{B}$  background events  $D^- \pi^+$  with  $D^- \rightarrow K_S^0 \pi^-$ . The extended likelihood function for all events is :

$$\mathcal{L} = \frac{\exp(-\sum_j n_j)}{N!} \prod_i \sum_j n_j \mathcal{P}_j^i, \quad (4)$$

where  $n_j$  is the yield of events of hypothesis  $j$  found by the fitter, and  $N$  is the number of events in the sample. The first factor takes into account the Poisson fluctuations in the total number of events.

We determine the PDFs for signal and  $B\bar{B}$  backgrounds from MC distributions in each observable. For the continuum background we establish the functional forms and initial parameter values of the PDFs with off-resonance data. We allow the signal  $a_1(1260)$  PDF parameters and the most important  $q\bar{q}$  background PDF parameters to float in the final fit. The distributions of invariant mass of  $a_1(1260)$ ,  $a_2(1320)$  and  $\pi(1300)$  in signal events are parameterized as relativistic Breit-Wigner line-shapes with a mass dependent width which takes into account the effect of the mass dependent  $\rho$  width. The  $m_{\text{ES}}$  and  $\Delta E$  distributions for signal are parameterized as double gaussian functions. Slowly varying distributions are parameterized by linear functions. The combinatoric background in  $m_{\text{ES}}$  is described by a phase-space-motivated empirical function [13]. We model the  $\mathcal{F}$  distribution using a Gaussian function with different widths above and below the mean. The A distributions are modelled using Gaussians in  $a_1^+(1260) \pi^-$  and polynomials in  $a_2^+(1320) \pi^-$  and  $\pi^+(1300) \pi^-$ .

## 4 RESULTS

We present the measurement of the branching fraction of the  $B$  decay to  $a_1^+(1260) \pi^-$ , considering  $a_2^+(1320) \pi^-$  and  $\pi^+(1300) \pi^-$  as sources of background. By generating and fitting simulated samples of signal and background events, we verify that our fitting procedure is working properly. We find that the minimum  $\ln \mathcal{L}$  value for the on-resonance data lies well within the  $\ln \mathcal{L}$  distribution from these simulated samples. Fits to data show no evidence of  $\pi^+(1300) \pi^-$ , since a negative yield is obtained for this resonance. For this reason the  $\pi^+(1300) \pi^-$  component has been left out in final fits to the yields.

The reconstruction efficiency is obtained from the fraction of signal MC events passing the selection criteria once corrected for a bias detected in the fit yield. This bias (about 6%) is determined

Quantity	$a_1^+(1260)\pi^-$
Signal yield	$867 \pm 85$
Reconst. $\epsilon$ (%)	19.8
$\prod \mathcal{B}_i$ (%)	50
Stat. sign. ( $\sigma$ )	18.5
$\mathcal{B}(\times 10^{-6})$	$40.2 \pm 3.9 \pm 3.9$

Table 1: Final fit results in  $B^0 \rightarrow a_1^+(1260)\pi^-$ . Fitted signal yield, the final reconstruction efficiency ( $\epsilon$ ), the daughter branching fraction product, the statistical significance, and the central value of the branching fraction with statistical and systematic errors.

from fits to simulated samples, each equal in size to the data and containing a known number of signal MC events combined with events generated from the background PDFs.

The fitted values of the  $a_1(1260)$  parameters are:  $m_{a_1} = 1.22 \pm 0.02$  GeV/ $c^2$  and  $\Gamma_{a_1} = 0.423 \pm 0.050$  GeV/ $c^2$ . In Table 1 we show the results of the fits for on-resonance data. The statistical error on the number of events is taken to be the change in the central value when the quantity  $-2\ln\mathcal{L}$  changes by one unit. The statistical significance is taken as the square root of the difference between the value of  $-2\ln\mathcal{L}$  for zero signal and the value at its minimum. In Fig. 1 we show the  $m_{ES}$ ,  $\Delta E$ ,  $m_{a_1}$  and A projections made by selecting events with a signal likelihood (computed without the variable shown in the figure) exceeding a threshold that optimizes the expected sensitivity.

## 5 SYSTEMATIC STUDIES

Most of the systematic errors on the yields that arise from uncertainties in the values of the PDF parameters have already been incorporated into the overall statistical error, since they are floated in the fit. We determine the sensitivity to the other parameters of the signal PDF components by varying these within their uncertainties. The result is shown in the first row of Table 2. This is the only systematic error on the fit yield; the other systematics apply to either the efficiency or the number of  $B\bar{B}$  pairs in the data sample.

The uncertainty in our knowledge of the efficiency is found to be  $0.8N_t\%$ , where  $N_t$  is the number of signal tracks. We estimate the uncertainty in the number of  $B\bar{B}$  pairs to be 1.1%. The fitting algorithm introduces a systematic bias of 2.8%, which was found from fits to simulated samples with varying background populations. Published world averages [2] provide the  $B$  daughter branching fraction uncertainties. The systematic error from  $a_1(1260)K$  cross-feed background is estimated to be 1.4%, while the systematic error due to SCF is found to be 3.5%. We also take into account systematic differences between data and MC for the  $\cos\theta_T$  selection (1.8%) and the possibility of interference between the  $a_1$  and  $a_2$  amplitudes (4%). The values for each of these contributions are given in Table 2.

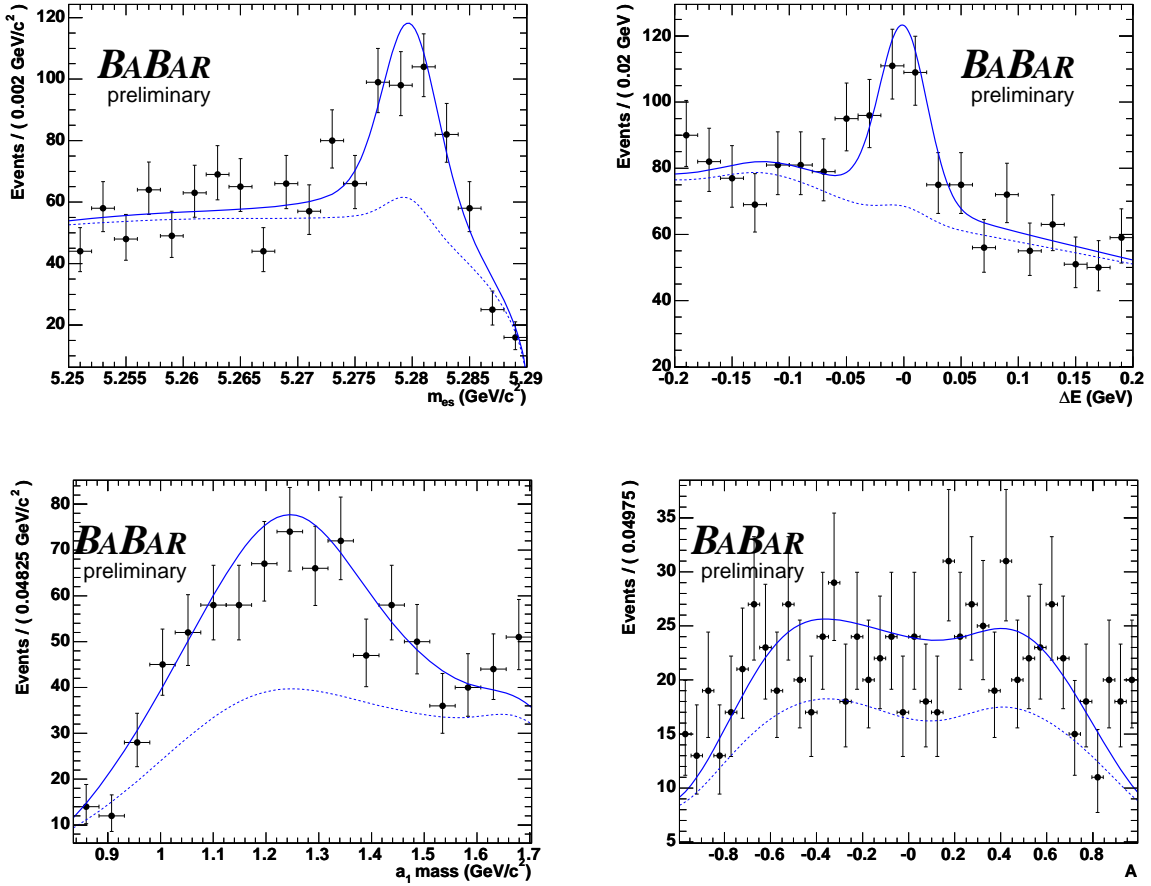


Figure 1: Projections of  $m_{ES}$ (a),  $\Delta E$ (b),  $a_1$  mass(c) and  $A$ (d) for  $a_1^+(1260)\pi^-$ . Points with errors represent data, dotted lines the background from continuum and  $B\bar{B}$  combined, solid curves the full fit functions. These plots are made with a cut on the signal likelihood and thus do not show all events in the data sample.

Quantity	$a_1^+ \pi^-$
Fit yield	6.2
Fit eff/bias	2.8
Track multiplicity	1.0
Tracking eff	3.2
Number $B\overline{B}$	1.1
SCF	3.5
$a_1 K$ cross-feed	1.4
MC statistics	0.6
$\cos \theta_T$	1.8
$a_1$ - $a_2$ Interf.	4.0
Total	9.6

Table 2: Estimates of the systematic errors (in percent).

## 6 SUMMARY

We have obtained a preliminary measurement of the branching fraction for  $B^0$  meson decays to  $a_1^+(1260) \pi^-$  with  $a_1^+(1260) \rightarrow \pi^+ \pi^+ \pi^-$ . The measured branching fraction is:

$$\mathcal{B}(B^0 \rightarrow a_1^+(1260) \pi^-) = (40.2 \pm 3.9 \pm 3.9) \times 10^{-6} \quad (5)$$

The fitted values of the  $a_1(1260)$  parameters are:  $m_{a_1} = 1.22 \pm 0.02$  GeV/ $c^2$  and  $\Gamma_{a_1} = 0.423 \pm 0.050$  GeV/ $c^2$ .

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